# A Study of the Source Mechanism of the Alaska Earthquake and Tsunami of March 27, 1964

## Part I. Water Waves[1]

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ABSTRACT: The geologic history and the general geomorphology of the area affected by the March 27, 1964 Alaska earthquake are given. The tsunami-generating area is determined and the extent of crustal displacement and the limits of the areas of subsidence and uplift, as revealed by geologic evidence, are discussed. The dimensions of this tsunami-generating area, its volume of crustal displacement, and the energy associated with the tsunami are calculated. Wave activity within and outside the generating area and the possible generating mechanisms for the tsunami are discussed. A wave refraction diagram of the Alaska tsunami for the north Pacific Ocean area is presented in Figure 6.

The Aleutian Island Arc and the Aleutian Trench extend for 2800 km from Kamchatka to south-central Alaska along remarkably smooth curves which are convex toward the south (Fig. 1). The Arc forms the Alaska Peninsula and, according to Wilson (1954), intersects, north of Cook Inlet, a second tectonic arc that extends northward from the vicinity of the Wrangell Mountains. However, Plafker (1965) regards this second segment as a continuation of the Aleutian Arc. Where the trench impinges on Alaska it loses its identity, although an offshore range of seamounts suggests it may once have extended around to the south to parallel the continental slope, as postulated by Menard and Dietz (1951). Concavity in the former shape of the trench on its eastern segment is also suggested by the sedimentary arc defined by Wilson (1954), which embraces Kodiak Island and the Kenai Peninsula. As shown by Wilson, such concavity is to be expected where two arcs meet at an acute angle, as is well exemplified where the Aleutian and Kuril-Kamchatka arcs intersect. It is also quite possible that large horizontal movements of crustal blocks have helped to change the shape of the Trench and Arc on their eastern segments. However, no such evidence was found in a field study following the Good Friday earthquake (Berg et al., in preparation).

The nature of the termination of the eastern segment of the Aleutian Trench is obscured by thick sediments washed in from the continental shelf against which it abuts offshore from Cape Suckling. The sediments are of geosynclinal-dimensions in the sedimentary arc on Kodiak Island (Menard and Dietz, 1951) and as shown by drilling on the Kenai Peninsula. Woollard et al. (1960) show there is geophysical evidence for at least 7 km of sediments in Cook Inlet, a graben separating the primary arc from the offshore sedimentary arc. Sediment is about 2 km thick off Kodiak Island along the Aleutian Trench, thinning out to about 0.7 km south of Unimak Island in the deep water area, according to seismic measurements by Shor (1962).

### THE GENERATING AREA OF THE ALASKA TSUNAMI

According to Van Dorn (1964), the tectonic dislocations associated with the Alaska earthquake of March 27, 1964 ranged over a distance of 800 km, from the upper portion of Prince William Sound to southwest of the Trinity Islands. The dislocations follow a dipole pattern of positive and negative displacements on either side of a zero-line which, intersecting the east coast of Kodiak Island, continues northeast to the western side of Prince William Sound. There, changing direction, it

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[1] Hawaii Institute of Geophysics Contribution No. 184. Manuscript received June 22, 1966.

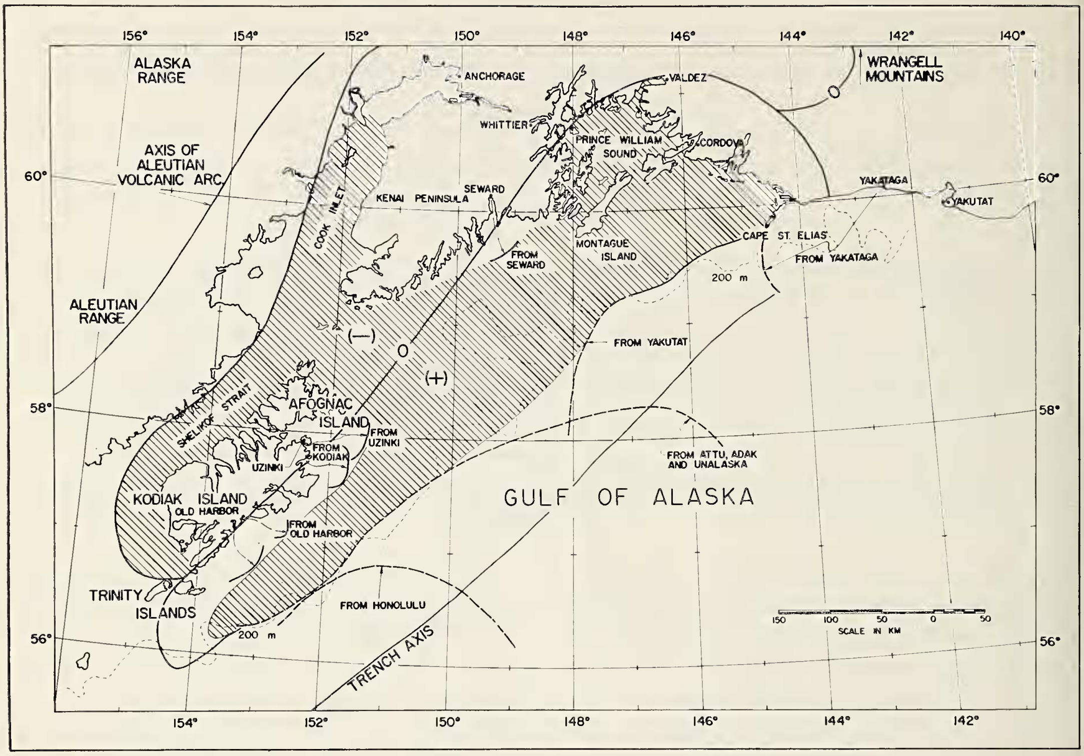

FIG. 1. Generating area of the Alaska tsunami. *Crosshatched area* indicates (—) area of subsidence and (+) area of uplift. *Heavy dashed lines* indicate the backward-refracted wave fronts. *Solid line marked by a zero* is the axis of rotation (no elevation change). *Other solid lines* indicate tectonic axes.

runs east along the upper part of the sound. The line roughly parallels the Aleutian Trench axis and separates the Kodiak geosyncline from the shelf geanticline.

The areas north and west of this line have undergone negative elevation changes, whereas the east and south underwent positive changes. An extensive pattern of positive surface dislocations under the sea is suspected to lie east of the island of Kodiak and along the continental shelf bordering the Gulf of Alaska. The extent of these dislocations still needs to be confirmed by detailed bathymetric surveys of the area, although large positive displacements have been observed as far south as Middleton Island and southwest to Sitkinak Island. Wave refraction studies, described here, also strongly indicated that the tsunami-generating area was mainly in the belt of uplift and included a large segment of the continental shelf and slope.

The zone between the known areas of tectonic uplift closely corresponds to a major crustal fault defined by crustal seismic measurements conducted by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington (Woollard et al., 1960). In view of the shallowness of the earthquake (20 km), it was concluded that the crustal dislocations occurred alongside a zone of tilting or a surface rupture (Grantz et al., 1964), but a survey of the area failed to identify such a feature. The focal depth corresponds, however, to the base of the granitic layer defined by Woollard's analysis of the crustal measurements made by the Carnegie Institution.

The total area of tectonic displacements associated with the Alaska earthquake of March 27, 1964 is estimated to be approximately 215,000 km². This is the largest area known to be associated with a single earthquake within historic time.

The magnitude of the Alaska earthquake was estimated to be from 8.4 to 8.75, which is greater than the 1906 San Francisco earthquake (8.3), and equal to or greater than the 1960 Chile earthquake (8.4). The epicenter of the earthquake was at 61.05°N, 147.7°W (USCGS, 1964), near the east shore of Unakwik Inlet in northern Prince William Sound.

Geological investigations have defined the land areas affected by the earthquake. To the east, the zone of deformation appears to die out between the Bering Glacier and Cape Yakataga. The northwestern limit of tectonic changes extends at least to the west side of Shelikof Strait and Cook Inlet (Plafker, 1965). The north inland limit is known only along the highway connecting Valdez and Fairbanks; it appears to extend in a northeasterly direction to the vicinity of the Wrangell Mountains, and quite possibly into the Alaska Range.

The area of uplift covers about 105,000 km$^2$ and extends from southern Kodiak Island northeast to Prince William Sound. It includes the southern and eastern parts of Prince William Sound, the coastal area as far east as the Bering Glacier, and the continental shelf and part of the slope to a depth contour of approximately 200 m. The maximum uplift on land was 10 m at the southwest end of Montague Island, but is suspected to have been considerably more offshore. Uplift also occurred along the extreme southeastern coasts of Kodiak Island and Sitkalidak Island, and part or all of Sitkinak Island. The maximum measured uplift of Sitkalidak Island was 0.4 m. The estimated uplift of Sitkinak Island was from 0.35 to 0.65 m and possibly as much as 1.5 m (Plafker, 1965).

The area that subsided included the northern and western parts of Prince William Sound, the western segment of the Chugach Mountains, portions of the lowlands north of them, most of the Kenai Peninsula, and almost all of the Kodiak Island group. This area of subsidence covers approximately 110,000 km$^2$, and is 800 km long and 150 km wide. Plafker (1965) estimates that the volume of crust that has been depressed below its pre-earthquake level is about 115 km$^3$.

The seaward limits of the earthquake and the tsunami-generating area were determined by means of a series of refraction diagrams based on Snell's Law of Refraction using the velocity equation for shallow water waves, $C = \sqrt{gd}$. Such a method of preparing refraction diagrams has shown good results, especially if carried out on large-scale charts with detailed bathymetry (Johnson, O'Brien, and Isaacs, 1948).

In constructing the refraction diagrams for the Alaska tsunami, the marigrams of different tide gauge stations around the Pacific were consulted and the total travel time of the first wave at each station was determined. Then refraction diagrams were constructed toward the earthquake area from each tide gauge station in lengths of time equal to the calculated travel time for that station. It was assumed that the last wave front in each refraction diagram would correspond to a point on the boundary of the generating area, and if enough refracted wave fronts from different stations were plotted, an envelope defining the tsunami-generating area could be drawn.

Wave fronts were refracted from Yakatat, Cape Yakataga, Seward, Uzinki, Kodiak, Old Harbor, Unalaska, Adak, Attu, and Honolulu. The last front of each of the refracted waves is shown by a heavy dashed line in Figure 1. The seaward boundary of the generating area is near the 200-m depth contour which defines the edge of the continental shelf. Maximum displacement of the ocean floor occurred along the continental shelf, from an area southeast of Kodiak Island, to an area close to Cape St. Elias south of the island of Kayak (Fig. 1). Geologic evidence, however, has shown positive land displacements as far north as Cape Suckling and as far east as the Bering Glacier. It is quite probable, therefore, that the tsunami-generating area extended farther to the northeast, although waves generated in such shallow water would reach tide gauges much later and their origin would not be identifiable.

Unfortunately, this same wave refraction technique could not be used to define the northern and western boundaries of the main tsunami-generating area, because conditions in Prince William Sound and elsewhere along the coast of Alaska were further complicated by local tsunamis, oscillations, and surge. In addition, no tide gauge stations were operating in the area, and personal accounts were conflicting as to arrival times of the different waves.

The northward limit is assumed to be restricted by the land boundaries, and the western limit to extend to the west side of Shelikof Strait and Cook Inlet.

In estimating the travel time of the tsunami, corrections were made for the delay at the island of Kodiak in the arrival of the ground shocks from Prince William Sound. These corrections ranged from 1 minute to 6 minutes and were based on the fact that the Navy Weather Central on the island of Kodiak listed the time of the principal shock in Prince William Sound as 6 minutes later than the time listed by the U. S. Coast and Geodetic Survey. This would imply that the wave front generated on the northeast side of the disturbance area had a 6-minute head start on the wave front generated southeast of Kodiak.

The tsunami-generating area covers an area 700 km long by 150 km wide, a total of about 105,000 km$^2$. The volume of the uplifted crust along the continental shelf is about 96 km$^3$. The energy associated with the tsunami has been estimated by Van Dorn (1964) to be of the order of $2.3 \times 10^{21}$ ergs. This estimate is based on the source dimensions of an area 240 nautical miles by 100 nautical miles and an uplift of 1.8 m (6 ft) at the northeastern end of this area and zero at the southwestern end. This estimate, however, is considered low because the generating area had dimensions that were larger than those estimated by Van Dorn.

Using our source dimensions, and assuming that the total energy was equal to the potential energy of the uplifted volume of water, the total energy for the tsunami in the Gulf of Alaska was calculated as follows:

$$
\begin{aligned}
E_t &= \frac{1}{6}\rho g h^2 A \\
&= \frac{1}{6}(1.03)(.980)(10^3)(10^4)(1.83^2)(1.5 \\
&\qquad \times 10^7)(7 \times 10^7) = 5.88 \times 10^{21} \text{ ergs}
\end{aligned}
$$

where

$E_t = E_p =$ total energy
$\rho = 1.03$ g/cm$^3$ = density
$g = 980$ cm/sec$^2$
$h =$ height of displacement = 1.83 m
$A =$ area
1 erg = g cm$^2$ sec$^{-2}$

The waves generated in the Gulf of Alaska were of an unusually long period, on the order of an hour or more. Their energy radiation was preferentially directed toward the southeast and this is why more damage was done to the North American coast than anywhere else east or south of the generating area. This preferential directivity of energy radiation can be attributed to the orientation of the tectonic displacements along the continental shelf of the Gulf of Alaska, and the long period of the waves can be related to the long seiche period of the shallow shelf.

According to Japanese seismologists (Iida, 1958), the generating area of a tsunami roughly corresponds to the distribution of the major aftershocks. This appears to be indeed the case in the Gulf of Alaska.

There were 52 aftershocks of the Alaska earthquake. The largest had a magnitude of 6.7. The aftershocks occurred in an area from about 15 km north of Valdez to about 55 km south of Trinity Islands, and were heavily concentrated on the northeast and the southwest of the uplifted region (USCGS, 1964), which also was the main tsunami-generating area.

The vast area of tectonic movements indicates that wave crests were generated along one or more line sources from the region of maximum uplift. Thus, the shores of the Kenai Peninsula were struck within 20 minutes after the start of the earthquake, and those of Kodiak Island, within 34 minutes.

Unfortunately, the violence of the earthquake left south-central Alaska without a tide gauge in operation. The only reliable record from the generating area is the one that was obtained by personnel of the U. S. Navy Fleet Weather Station at Kodiak; it is shown in Figure 2. This record has been corrected for the 1.7-m (5.6-ft) submergence of the area.

Outside the immediate generating area, the record of Cape Yakataga, as constructed from the personal account of C. R. Bilderback, a resident of the area, is the next most reliable record. This record is the only one obtained outside the generating area that shows an initial drop in the water level (Berg et al., in preparation). Withdrawal of the water immediately following the earthquake has been reported from Kayak, Middleton, and Hinchinbrook islands, as well as from Rocky Bay and Nuka Bay, at the end

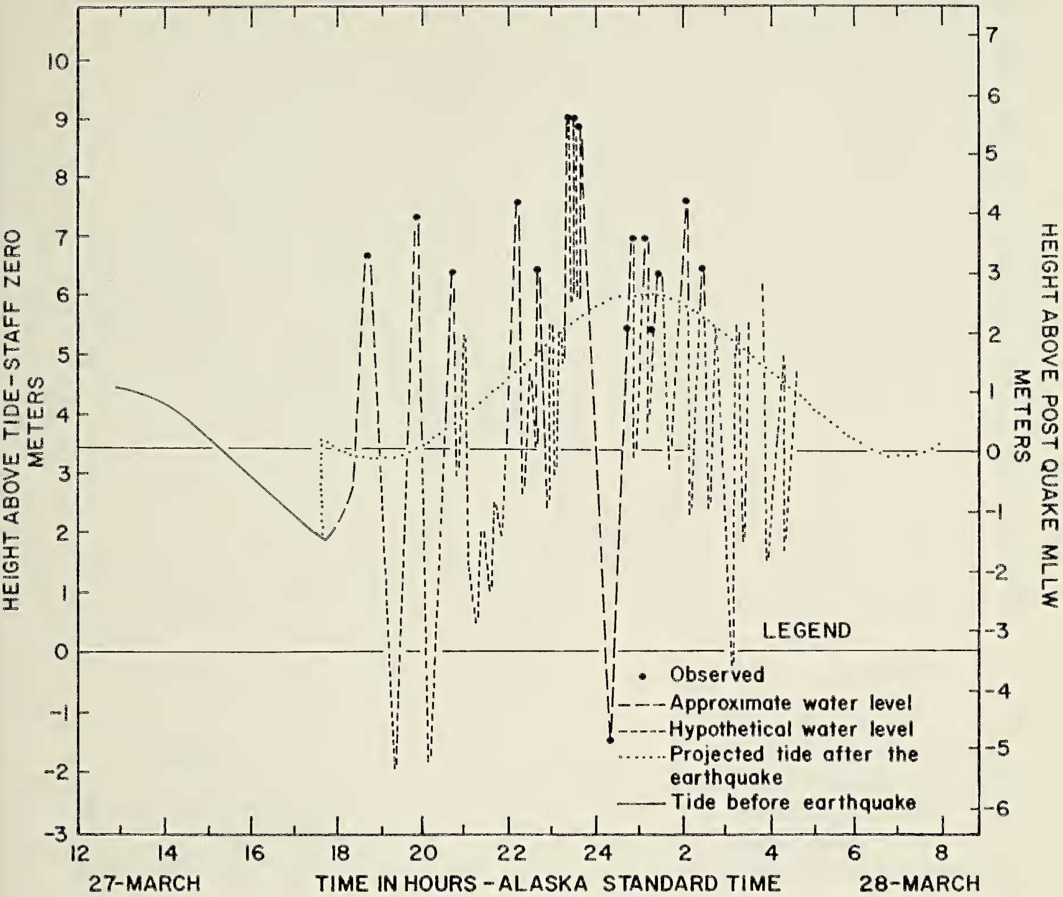

FIG. 2. Diagram of wave activity at Women's Bay, Kodiak Island. (From visual observations made at Marginal Pier, Nyman Peninsula.)

of the Kenai Peninsula, but these islands are inside the generating area.

Yakatat, a coastal town 170 km southeast of Cape Yakataga, had a tide gauge in operation, and the marigram shows that a positive wave arrived first (Fig. 3).

It is quite possible, therefore, that the first waves to arrive at Cape Yakataga had a different origin from that of the first waves to arrive at Yakatat. It could very well be that the Cape Yakataga waves traveled over the shallow portion of the shelf, whereas the Yakatat waves came from the open ocean.

An interesting aspect of these two records is that of the difference in amplitude and period of the first waves to arrive at these two sites—which also supports the hypothesis of difference in origin (see Figs. 3 and 4).

## TSUNAMI GENERATED IN PRINCE WILLIAM SOUND

The shallow continental shelf and the islands bordering the southern side of Prince William Sound, as well as the pattern of crustal displacements, confined the waves generated in this area to the Sound itself; very little energy escaped this closed region. Most of the energy was expended in the narrow, deep fjords of the Sound, creating catastrophic waves and setting up resonating oscillations and surges that lasted for hours. In certain places maximum inundation occurred 5 or 6 hours later, at high tide. At Valdez, for example, the third wave came in at 2300, March 27, and the fourth one at 0145, March 28 (Brown, 1964). This last wave took the form of a tidal bore and inundated the

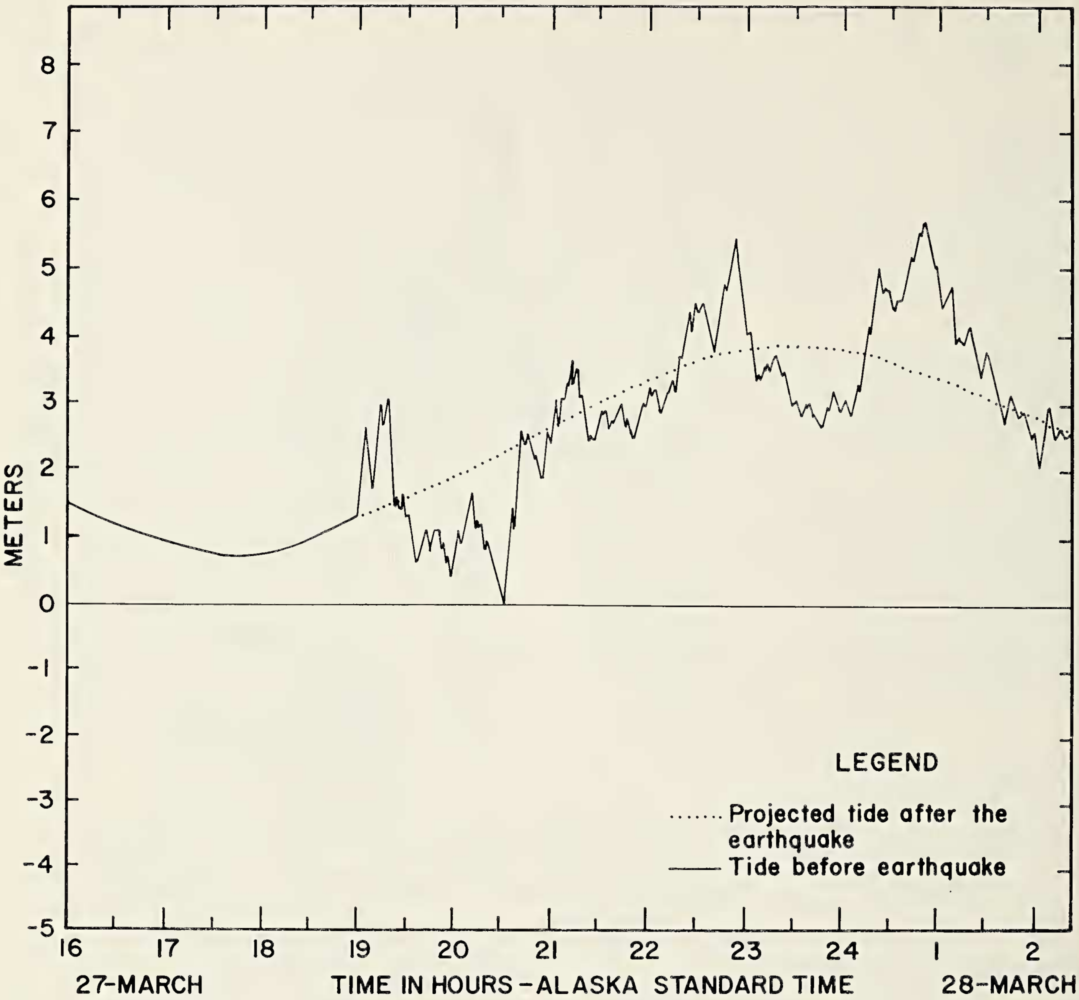

FIG. 3. Marigram of wave activity at the town of Yakutat.

downtown section of Valdez, ruining almost all the merchandise in the stores. These waves could not have come from the generating area outside Prince William Sound because if this were so, it would have taken them only 34 minutes to reach Valdez. It is more likely, then, that the waves at Valdez arrived in resonance at high tide, from the immediate area of Port Valdez.

Maximum positive crustal displacement in Prince William Sound occurred along the northwest coast of Montague Island and in the area offshore. These earth movements caused a gradient in hydrostatic level and the resulting short-period wave raced through Knight Island Passage within 10 minutes and on toward Chenega Island, inundating the village of Chenega to an elevation of 15.5 m and completely destroying it. This same wave continued north through Knight Island Passage and inundated Perry and Naked islands, but to lesser heights (Berg et al., in preparation).

Bathymetric surveys by the USCGS (1964) in the area off Montague Island and at the north end of Latouche Island revealed a number of large submarine slides. It is possible, therefore, that the combination of submarine slides and the tilting of the ocean floor due to uplift created the solitary wave reported at Chenega village and at Perry and Naked islands.

A second wave about 40 m high (125 ft) was reported coming out of the Valdez Narrows

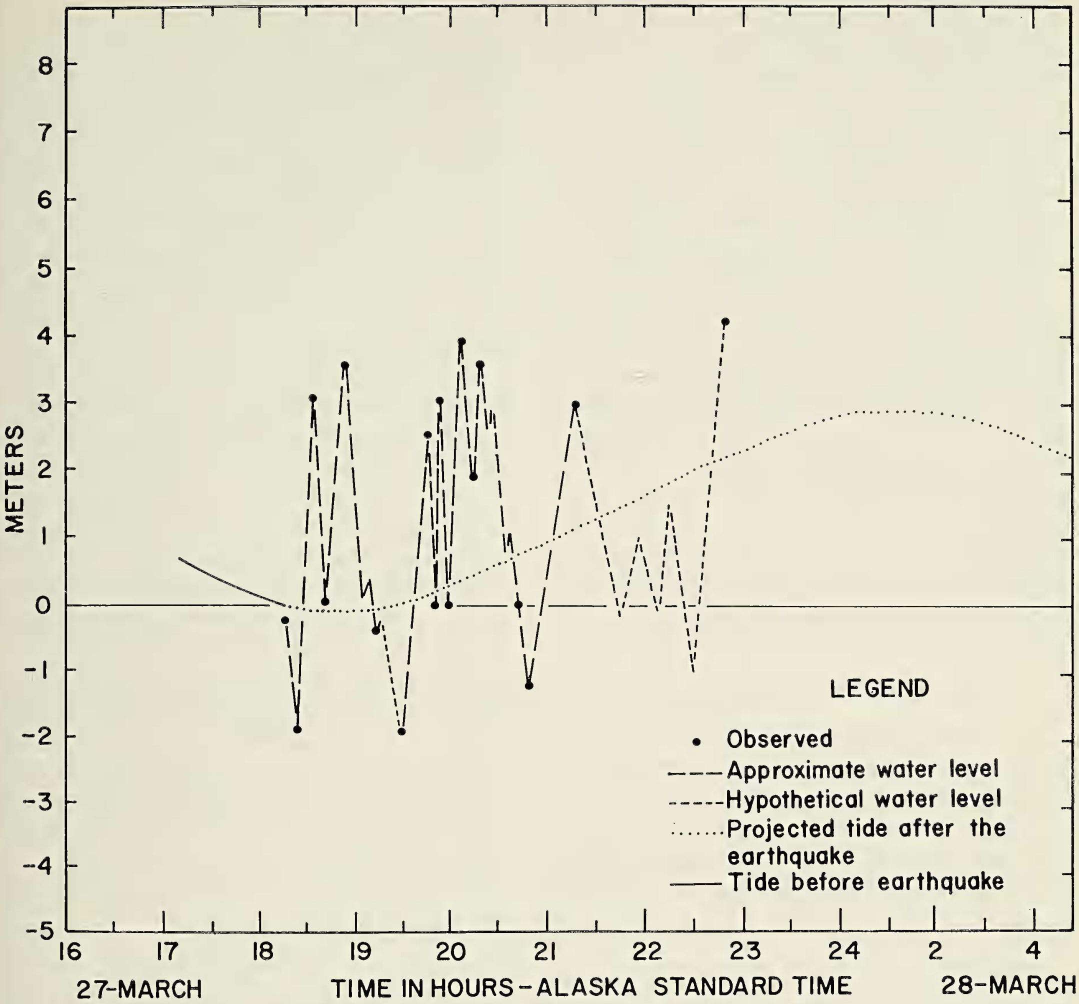

Fig. 4. Diagram of wave activity at Cape Yakataga.

and spreading across the Sound (Plafker and Mayo, 1965). This wave was caused by slumping of the glacial deltas in Port Valdez which had been shaken loose by the force of the earthquake.

## TSUNAMI MECHANISM

Most tsunamis result from earthquakes having focal depths of less than 60 km. Iida (1958) has derived an empirical relation giving the maximum focal depth H (in km) for an earthquake of magnitude M which has resulted in a detectable tsunami:

$$M = 6.42 + 0.01\ H \qquad (1)$$

where M is the Richter magnitude given by

$$\log E(\text{ergs}) = 11.8 + 1.5\ M \qquad (2)$$

The focal depth of the Alaska earthquake was about 20 km. This was shallow enough to create tsunami waves even though the epicenter of the main shock was as much as 100 km inland from the coast. A number of shallower aftershocks over a large area ranging from Hinchinbrook Island to southeast Kodiak Island indicate that crustal movements over a wide area were involved. Undoubtedly these shallow aftershocks created smaller waves that could not be separated, in the tide gauge records, from reflections of the initial tsunami.

If the tsunami waves that hit the island of Kodiak were the result of crustal movements only, then the first wave could be expected to be the highest, at least within the generating area. At Uzinki, Kodiak City, Women's Bay, and elsewhere on the island of Kodiak, however, the third and fourth waves were the highest. A theory of generation from a single pattern of crustal deformation is therefore not satisfactory here. Such factors as reflection from coastal boundaries, wave interaction, and resonance should be taken into consideration.

Slumps or avalanches, similar to the ones that occurred in Prince William Sound, are usually localized; they can produce no large tsunamis that would travel across wide portions of the ocean. According to Wiegel (1954), not more than 2% of the potential energy of a falling or sliding body is converted into wave energy. In Prince William Sound, however, slumping and sliding when added to tectonic movements created tsunami waves of very large energy, but their effect was catastrophic only locally; very little of the energy escaped the Sound.

## SUMMARY AND CONCLUSIONS

The Alaska earthquake of March 27, 1964 affected an area of approximately 215,000 km$^2$, extending from the Wrangell Mountains at the northeast to the Trinity Islands in the southwest, and from the west side of Shelikof Strait and Cook Inlet east to the vicinity of the Bering Glacier.

Geologic evidence has revealed a dipole pattern of positive and negative tectonic movements resulting from this earthquake. The area of subsidence covers approximately 110,000 km$^2$ and the volume of crust that has been depressed below its pre-earthquake level is about 115 km$^3$.

The area of uplift covers about 105,000 km$^2$ and includes the southern and eastern parts of Prince William Sound, the coastal area as far east as the Bering Glacier, and a great part of the continental shelf and slope bordering the Gulf of Alaska.

The seaward limits of the area affected by the Alaska earthquake and the tsunami-generating area were determined by means of a series of wave refraction diagrams as shown in Figure 5, based on Snell's Law of Refraction. The tsunami-generating area covers 140,000 km$^2$ and includes the whole of the region of uplift and part of the region of subsidence. It extends from the Trinity Islands to the Bering Glacier and includes Shelikof Strait, Cook Inlet, and the continental shelf bordering the Gulf of Alaska to a depth of approximately 200 m. The total volume of displaced material in the tsunami-generating area was estimated to be 120 km$^3$, and the energy associated with the tsunami was calculated to be in the order of $6 \times 10^{21}$ ergs.

As a result of this work the following conclusions are drawn:

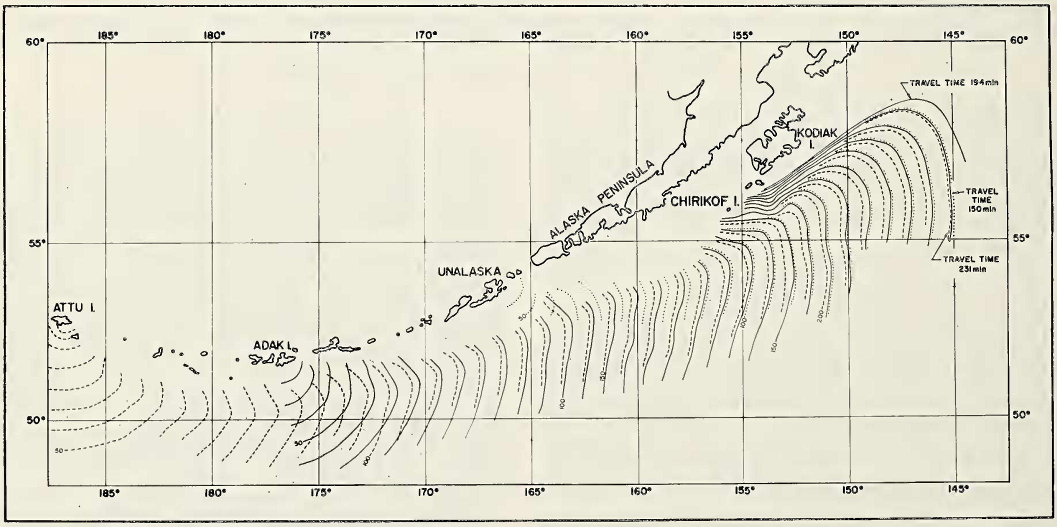

FIG. 5. Diagram of wave fronts refracted toward the earthquake area from Attu Island (*dashed line*), Adak Island (*solid line*), and Unalaska Island (*dotted line*).

1. Two main tsunami-generating areas can be distinguished: one along the continental shelf bordering the Gulf of Alaska; the other in Prince William Sound.
2. The main generating area in the Gulf of Alaska roughly corresponds to the geographic distribution of the major aftershocks.
3. The energy of the tsunamis generated in Prince William Sound was expended inside the Sound; not much energy escaped this closed region.
4. The long period of the waves generated in the Gulf of Alaska is related to the long seiche period of the shallow shelf.
5. The preferential radiation of energy toward the southeast is attributed to the orientation of the tectonic displacements along the continental shelf of the Gulf of Alaska.
6. The waves arriving at Cape Yakataga had their origin in the shallow coastal area near the Bering Glacier, whereas the waves arriving at Yakatat traveled through the deeper waters.
7. In Prince William Sound two major tsunamis were distinguished: one had its origin near the west coast of Montague Island, the other originated in the Port of Valdez.
8. Two types of tsunami-generating mechanisms were associated with the Alaska earthquake: (a) waves generated directly by tectonic movements of the sea floor, and (b) waves generated indirectly from landslides, mudflows, and slumping of alluvial deposits.
9. In Prince William Sound both generation mechanisms were evident, while in the generating area along the Gulf of Alaska, the generated tsunami was the direct result of tectonic movements.

## ACKNOWLEDGMENTS

The work on which this paper is based was supported in part by the National Science Foundation under the United States–Japan program for cooperative research in the Pacific, through grant No. GF-153, and in part by the Office

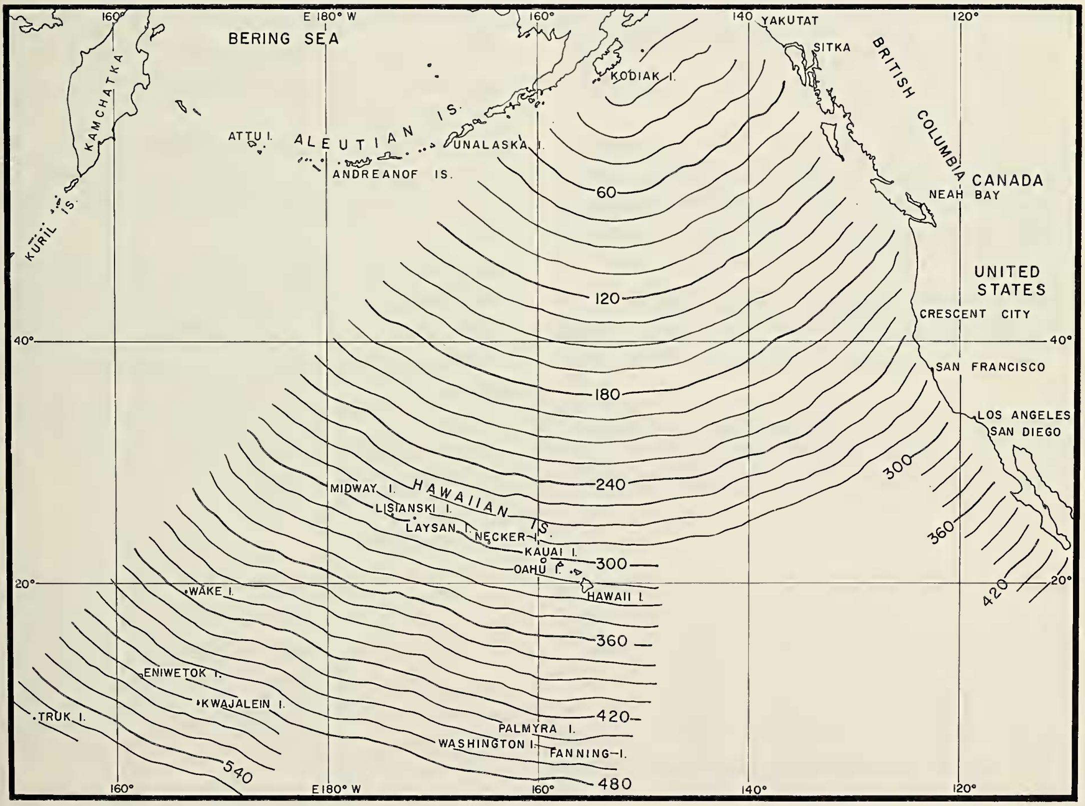

FIG. 6. Wave refraction diagram of the Alaska tsunami for the north Pacific Ocean (time interval: 15 minutes).

of Naval Research through contract Nonr-3748(03).

I am particularly indebted to D. C. Cox, W. M. Adams, and G. P. Woollard for their advice and constructive criticism.

I would also like to acknowledge with appreciation the advice, comments, and suggestions given to me by A. S. Furumoto, K. Kajiura, G. W. Groves, H. G. Loomis, G. R. Miller, and Robert Harvey.

I also thank the members of the United States–Japan Cooperative Field Survey (E. Berg, D. C. Cox, A. S. Furumoto, K. Kajiura, H. Kawasumi, and E. Shima) for permission to use data from their report prior to publication.

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